

THE MELTING OF GABBRO  
UP TO 45 KILOBARS\*

*E. Azmon*

---

E. Azmon, Principal Investigator

*J. W. Moyer*

---

J. W. Moyer, Director  
Physical Sciences

\*Portion of NASA Contract NAS-7-358 to Northrop Corporation

# THE MELTING OF GABBRO UP TO 45 KILOBARS\*

By

Emanuel Azmon

Northrop Corporation

## ABSTRACT

The melting range of natural gabbro has been determined at pressures up to 45 kilobars, using single-stage piston-cylinder apparatus and Pt-Pt-10 Rh thermocouples. The melting range is described by two curves which approach straight lines and can be defined as  $T_{\text{solidus}} = 1095 + 7.82P$  and  $T_{\text{liquidus}} = 1370 + 3.06P$ , where  $T$  is temperature in degree Celsius and  $P$  is pressure in kilobars. At 58 kilobars and  $1550^{\circ}\text{C}$  the two curves join, forming a single melting curve. The genetic state of the rock, which can be defined as the temperature-pressure history of the process affecting the rock prior to quenching, determines whether the quench product will remain gabbro or will be obsidian, basalt, porphyry, or vitrophyric porphyry.

## INTRODUCTION

The determination of mineral melting relations as a function of pressure provides important information regarding solidus-liquidus relations for a naturally occurring rock system. These P-T relations, combined with any proposed geothermal gradient for the earth, may be used to estimate the several possible depths where magma is generated and also estimate the composition of the magma, or, if below melting, estimate the crystallographic phases and the degree of crystallization. In correlating the laboratory high pressure-temperature experiments with the natural environment, however, it is important to remember that the origin of rocks usually takes place in an open large system (Azmon, 1965), in many cases at nonequilibrium and often at dynamic equilibrium (Azmon, 1963) or at mosaic equilibrium (Korzhinskiy, 1962).

\*Portion of NASA Contract NAS-7-358 to Northrop Corporation,  
Principal Investigator, E. Azmon

The gabbro group of important and diversified hypabyssal and plutonic rocks forms a continuation of the series granite-diorite, to which it is related by the decreasing content of  $\text{SiO}_2$ , increase in content of dark minerals and the appearance of olivines as important constituents. These rocks represent cooling and consolidation under pressures and temperatures which prevail in the depth of the earth. Textures are typically xenomorphic granular where the minerals are not bounded by their own crystal faces but have their outline impressed on them by adjacent minerals.

The study of melting of a crystalline gabbro rather than that of a glass of gabbroic composition was intended to determine conditions under which this gabbro is stable and conditions under which this gabbro would transform into other rocks.

#### STARTING MATERIAL

The gabbro used for this study was collected from Horton County, Quebec, and is one in a whole range of rock composition that would qualify as gabbro. The petrological composition of the gabbro is as follows: LABRADORITE -- 45 percent, well twinned,  $\text{AB}_{35}\text{An}_{65}$ ,  $N$  (index of refraction) = 1.562 in (001) cleavage plane, rodlike inclusions of opaque and non-opaque minerals; PYROXENE -- 50 percent, irregular grains of augite (diplage) with inclusions of opaque minerals, mixed with green serpentized OLIVINE and with clear highly fractured olivine grains filled with magnetite; ACCESSORIES -- 5 percent, coronas of pleochroic hypersthene, pale green amphibole, brown hornblende, calcite in veinlets cutting the labradorite.

#### APPARATUS

The experiments with the melting of gabbro at high pressures and temperatures were conducted with a Transis-tronics kiloton hydraulic press of the piston-cylinder type related in design to the devices described by Coes (1962), Hall (1958), and Boyd and England (1960) and is most similar to that used by Kennedy and LaMori (1961). This apparatus was used by Sterrett (1962) for the study of transformation in iron at high pressures. The total uncertainty in pressure determination is, according to him,  $\pm 1$  Kb. The presence of a temperature gradient in the graphite furnace and along the sample, and temperature fluctuation during experiments combine to give a temperature uncertainty of  $\pm 10^\circ\text{C}$ . The temperature gradient along the graphite furnace is almost symmetrical with the hottest spot close to the center.

Two experimental assemblies were used as shown in Figure 1. The first assembly consists of the parts listed in Figure 1a, with a Differential Thermal Analysis (DTA) arrangement of the thermocouples. It was hoped that phase changes occurring near the upper tip of the platinum capsule would show on the DTA curve and would be correlated with the petrographic identification. However, the great detail and number of fluctuations in the curve made it very difficult to correlate these data with specific change in the complex samples. A distinct thermal gradient developed in the capsules from top to bottom where the hot end was on top. This gradient permitted phase changes to occur in portions of the samples and the transition into unchanged sample could be examined petrographically (Fig. 2). The transition temperature was then estimated on the basis of distance from the thermocouple and the experiment was repeated using a second assembly and the estimated temperature as a guideline. The second assembly consists of parts listed in figure 1b, using a very small sample to minimize the thermal gradient, and thermocouples on both upper and lower ends of the sample.

#### PROCEDURE

The reaction capsules containing the sample and the rest of the assembly were kept in a drying oven at  $110^{\circ}\text{C}$  prior to each experiment to prevent lowering of the "dry" melting temperatures by absorbed water. The platinum capsules were left unsealed to permit any trapped moisture to escape soon after the temperature of the furnace exceeded  $100^{\circ}\text{C}$ .

Quenching was attained by cutting off the power supply to the furnace. Figure 3 shows the temperature drop as function of time using three different set-ups for insulation. The 1/2 inch diameter talc sleeve was adopted as an outer sleeve for all the experiments since it allowed the most effective quench. Temperature dropped to below  $500^{\circ}\text{C}$  in 6 to 10 seconds. The capsule was removed from the assembly and cut longitudinally into two parts, one part for x-ray work and the other for thin section petrographic study. For correlation of the petrographic observations with the temperature readings only the area immediately next to the thermocouples was considered (the area which fell within an imaginary circle about the thermocouple tip as a center, and the distance from the tip to the capsule sidewall as a radius).

## DETERMINATION OF THE MELTING CURVE

Run data for the melting of gabbro are listed in Table 1. Melting of a complex substance like gabbro is not a simple transformation of a solid into a liquid. It occurs over a range of temperatures and it is gradual. Some of the components, like the feldspars, may melt first as individual minerals or eutectically. Others, like the pyroxenes and olivines, may melt next as individual minerals, or eutectically, or they may dissolve in the feldspar melt below their own melting temperatures. The criteria for recognizing melting after the temperature quench is a problem by itself, since several characteristics can develop in the sample during the process. The application of pressure to a core sample may crush the granules into fine grain, uniform-looking material. This pulverization depends on the mechanical characteristics of the sample and the applied pressure and involves no melting. At elevated temperature below the melting range, recrystallization can take place in the solid state. The re-crystals are coarser grained than the original crystals and distinctly different (Fig. 2) but they should not be taken as a criterion for melting. Three criteria were used to recognize evidence of melting in the quench product, the presence of glass, vesiculation (Fig. 4) and the presence of needle-like quench crystals (Fig. 5). The glass forms when a molten rock is quenched since the kinetics of recrystallization are too slow to allow orderly arrangement of crystals. The needle-like crystals form out of the same melt but at higher temperatures or pressures. Their maximum length is approximately 600 microns and their width approximately 15 microns. Vesiculation forms at one atmosphere pressure when trapped gases in quenched magma support the structure of the cavity in which trapped. The vesicles range in diameter from several microns up to 375 microns. It is conceivable that their upper limit is controlled primarily by the dimensions of the sample.

Liquid gabbro can be quenched to vesicular matter over the entire range of melting at one atmosphere pressure. Above one atmosphere and below approximately 25 kilobars (25000 atmospheres) there are three temperature regions (Fig. 6): one, where liquid gabbro quenched into glass coexists with original unaltered crystals; two, at higher temperatures the glass coexists with recrystallized material forming a vitrophyric porphyry; three, at still higher temperatures only the glass exists as obsidian. Above 25 kilobars, the region of glass and unaltered crystals does not exist; the vitrophyric porphyry changes into quench crystals and recrystallized original crystals forming a porphyry; and the obsidian glass gives way to quench crystals forming basalt.

A qualitative reconfirmation of the existence of these temperature and pressure regions can be observed in the analyses of those capsules which display a thermal gradient. For example, sample number 123 (Table 1) was run at 20 kilobars with the thermocouple recording 1450°C at the hot end where the original crystalline material had all transformed into glass. On the "cold" end the temperature is not known, however, the presence of relics of the original crystals indicates a temperature lower than 1360°C (Fig. 6). Between the ends, the analysis shows quench crystals. Examination of areas in Figure 6 which are intersected by a line at 20 kilobars extending from 1450°C to 1360°C, suggests that sample 123 should contain: glass, quench crystals, re-crystals or more glass, and original crystals. Another example is sample 129 (Table 1) which was run at 40 kilobars with the thermocouple recording 1550°C at the hot end where the original crystalline material had all transformed into quench crystals. The transition towards the cold end in this sample is first into re-crystals and second into original crystals, with no glass at all. This is in agreement with what would be indicated by examination of figure 6.

Normally, when conducting experiments at high-temperature-high-pressure, one should expect the capsule material to participate in the reaction and contaminate the sample causing a change in its melting behavior. Contamination was expected more in the use of boron nitride capsules than in the use of platinum capsules because for the large scale manufacturing of boron nitride the process requires boric oxide, calcium phosphate, water, ammonia, and other compounds (Ingles and Popper, 1960). As a result, the end product "pure" boron nitride has a binder of boric acid ( $B_2O_3 \cdot xH_2O$ ) of 3 to 5 weight-percent (Hsu, 1967). Thus "fluxing effect" may be caused by boron nitride. However, in comparing the data obtained from the platinum capsules with that obtained from the boron nitride capsules it was not possible to isolate the suggested effect of the latter.

The melting range constructed from the data in Table 1 is shown in figure 6 as the area between the solidus and the liquidus curves. At one atmosphere this range spans over 275°C from 1095°C up to 1370°C. At 45 kilobars the range is only 65°C, from 1445°C to 1510°C. These curves approach straight lines defined by the equations,  $T_{solidus} = 1095 + 7.82P$  and  $T_{liquidus} = 1370 + 3.06P$ , where  $T$  is temperature in degree Celcius and  $P$  is pressure in kilobars. Extrapolating the solidus and liquidus to higher pressures, the two curves join at 58 kilobars and 1550°C forming a single melting curve. The only indication of the expected plagioclase high pressure transformation (Green and Lambert, 1965) is the presence of garnet in two samples (Table 1).

## ROCK FORMING PROCESSES AT ELEVATED PRESSURES AND TEMPERATURES

Rock forming processes in nature take place in open large systems, as indicated in the introduction, which may involve a whole mountain or a mountain range and where several reactions may take place simultaneously and yet be geographically remote from each other, thus resulting in a mosaic equilibrium in the system. Nevertheless, it is possible and common in the geologic realm that such a complex system with its range of compositions and of textures would fit into a category of a specific rock, for example: obsidian, basalt, gabbro, or: porphyry, vitrophyric porphyry. Figure 6 displays a system of that complex nature. Superimposed on the phase diagram illustrating the solidus and liquidus curves in Figure 6 it was necessary to show additional curves separating between states of the system which quench into distinct rocks. These states can be referred to as genetic states, and the figure as a genetic diagram. The genetic diagram displayed in Figure 6 shows several temperature-pressure areas where the gabbro used as an initial sample would quench into new rocks.

### CONCLUSIONS

Although a melting point of a rock like gabbro does not exist in the true physico-chemical sense, a melting range can be defined and delineated with a solidus and a liquidus curve. The processes that take place between these two curves at elevated temperatures and pressures are multiple and complicated. However, below the solidus, the rock complex is a true solid and above the liquidus it is a true liquid. The type of rock that will be generated by quenching, is determined by the genetic state of the system prior to quenching.

### ACKNOWLEDGMENT

The author would like to acknowledge Mr. G. C. Deutsch and Mr. J. Gangler of NASA Office of Advanced Research and Technology and the management of Northrop Systems Laboratories who made it possible to accomplish the above as a part of a research on beneficial uses of lunar rocks. We would like to thank Dr. R. Gaal for doing a portion of the petrographic analyses and Dr. R. D. Tooley for his critical review of this paper. We would also like to thank Mr. R. R. Berlot, Dr. K. F. Sterrett, and Dr. J. Bledsoe, whose consecutive efforts made the continuation of the experiments possible. And last, but not least, many thanks to Mr. Oliver Meier who, as a research assistant, gave the critical help required to develop the techniques for sample preparation, run, and analysis.

## REFERENCES

- Boyd, F. R. and England, J. L. (1960) Apparatus for Phase Equilibrium Measurement at Pressure up to 50 Kilobars and Temperature up to 1750°C, Jour. Geoph. Res., Vol. 65, pp. 741-748.
- Coes, L. (1962) Synthesis of Minerals at High Pressure, Chap. 7, Modern Very High Pressure Techniques, Butterworth, Washington, pp. 137-150.
- Green, D. H. and Lambert, I. B. (1965) Experimental Crystallization of Anhydrous Granite at High Pressures and Temperatures, Jour. Geoph. Res., Vol. 70, No. 20, pp. 5259-5268.
- Hall, H. T. (1958) Some High Pressure Apparatus Design Considerations; Equipment for Use at 100,000 Atmospheres and 3000°C, Rev. Sci. Inst., No. 29, pp. 267-275.
- Hsu, L. (1967) The Melting of Fayalite up to 40 Kilobars, (In print, Jour. Geoph. Res.)
- Ingles, T. A. and Popper, P. (1960) The Preparation and Properties of Boron Nitride, Chap. 8, Special Ceramics, proc. symp. British Ceramic Res. AMOC., Academic Press, N.Y., pp. 144-167.
- Kennedy, G. C. and LaMori, P.N. (1961) Some Fixed Points on the High Pressure Scale, Conf. of Very High. P., Lage George, N.Y., June 1960, John Wiley and Sons.
- Sterrett, K. F. (1962) The  $\alpha$ - $\gamma$  and  $\gamma$ - $\alpha$  Transformation in Iron at Ultra-high Pressures, Northrop Space Laboratories, TM 62-223.

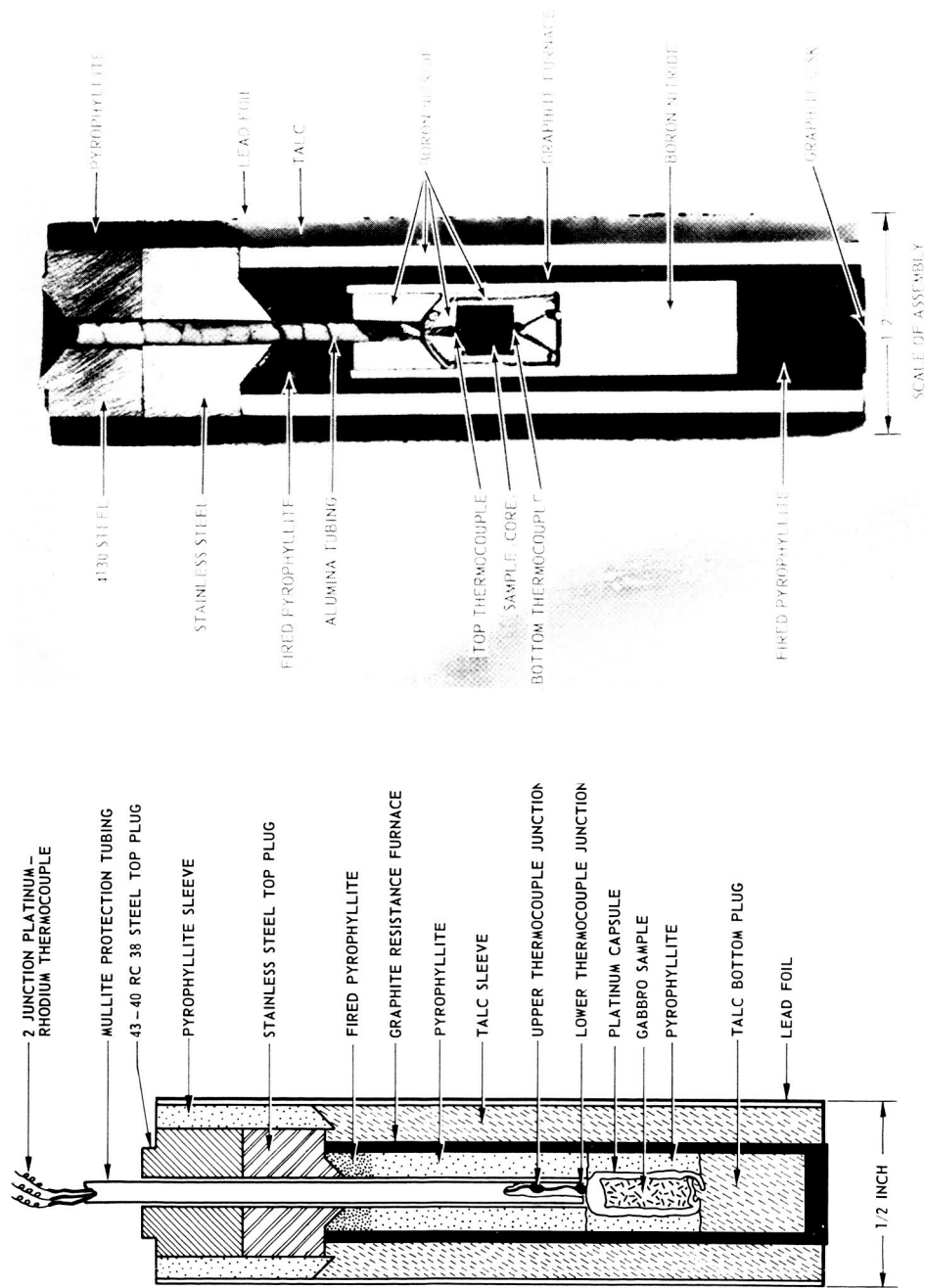


TABLE 1  
RUN DATA FOR MELTING OF GABBRO

RUN NUMBER	SAMPLE	CAPSULE	P KB	T°C	TIME Sec	COMMENTS
148	powder	Pt	.001	1100	60	Unaltered crystal + trace of glass
149	"	"	"	1200	"	Glass + relic crystals; vesicular
150	"	"	"	1300	"	Glass + trace of re-crystals
133	"	"	.001-2	1370	"	Glass + relic crystals
266 top	core	BN	11	1100	300	Original crystals
" bot.	"	"	"	1310	"	Glass + relic crystals
265 top	"	"	"	1185	"	Mixed glass and original crystals
" bot.	"	"	"	1210	"	Glass around original crystals
143	powder	Pt	10	1200	50	Mixed glass and original crystals
277	core	BN	"	1250	90	Glassy periphery around original crystals
262	"	"	"	1290	300	Glass
274 top	"	"	"	1295	"	Glass and relic crystals
" bot.	"	"	"	1410	"	Glass (quench crystals between top and bot.)
264	"	"	"	1333	"	Glass + relic crystals

RUN NUMBER	SAMPLE	CAPSULE	P KB	T°C	TIME Sec	COMMENTS
270	core	BN	10	1350	300	Glass + relic (less glass toward cold end)
142	powder	Pt	"	1370	90	Glass + re-crystals
269 top	core	BN	"	1375	300	Glass
" bot.	"	"	"	1500	"	Glass
272	"	"	"	1525	210	Glass
152 top	"	"	16½	1393	300	Glass (relic crystals away from hot end)
" bot.	"	"	"	1455	"	Glass
111	powder	Pt	20	1345	540	Glass + re-crystals
132	"	"	"	1395	45	Glass + re-crystals
136	"	"	"	1430	19	Quench crystals + glass + re-crystals
123	"	"	"	1450	7	Glass (toward cold end: quench crystals, glass, relic crystals)
141	"	"	32	1430	45	Quench crystals + re-crystals
126	"	"	30	1470	60	Quench crystals
125	"	"	30	1475	53	Quench crystals (relic crystals toward cold end)

RUN NUMBER	SAMPLE	CAPSULE	P KB	T°C	TIME Sec	COMMENTS
137	powder	Pt	35	1480	25	Quench crystals (relic crystals toward cold end)
134	"	"	40	1350	~1	Original crystals
128	"	"	"	1430	~1	Quench crystals transition into re-crystals. Garnet
138	"	"	"	1480	16	Quench crystals (+ re-crystals?)
129	"	"	"	1550	79	Quench crystals (re-crystals and relic crystals on cold end)
151 top	Core	BN	48	1280	10	Original crystals
" bot.	"	"	"	1350	"	Original crystals
130	Powder	Pt	45	1430	63	Original crystals. Garnet(?)
147	"	"	"	1500	38	Quench crystals in matrix of re-crystals
131	"	"	"	1590	3.5	Quench crystals (Original crystals on cold end)



a. A DTA ARRANGEMENT OF THE THERMOCOUPLES IN A PLATINUM CAPSULE

b. A CORED SAMPLE IN A BN CAPSULE WITH THERMOCOUPLES ON BOTH UPPER AND LOWER ENDS OF THE SAMPLE

FIGURE 1 TWO HIGH PRESSURE EXPERIMENTAL ASSEMBLIES

0 1 2  
MM SCALE

QUENCH  
CRYSTALS →

RECRYSTALS →

ORIGINAL  
CRYSTALS →



FIGURE 2 A TYPICAL TRANSITION IN GABBRO FROM ORIGINAL CRYSTALS, TO RECRYSTALS, TO QUENCH CRYSTALS (AZ129)

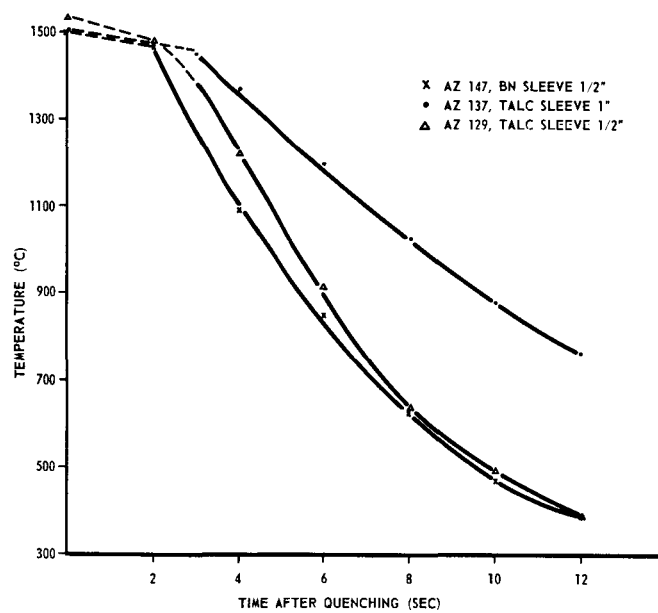


FIGURE 3 TEMPERATURE DROP IN A REACTION CAPSULE AS FUNCTION OF TIME USING THREE DIFFERENT SETUPS FOR INSULATION

0 1 2  
MM SCALE

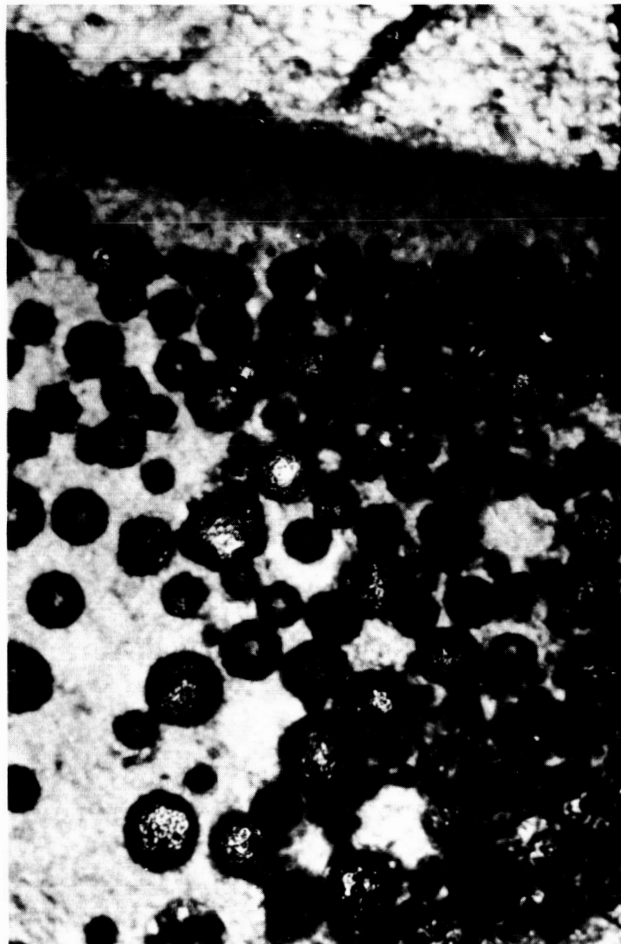


FIGURE 4 VESICLES IN GLASS MATRIX

0 500  $\mu$   
SCALE

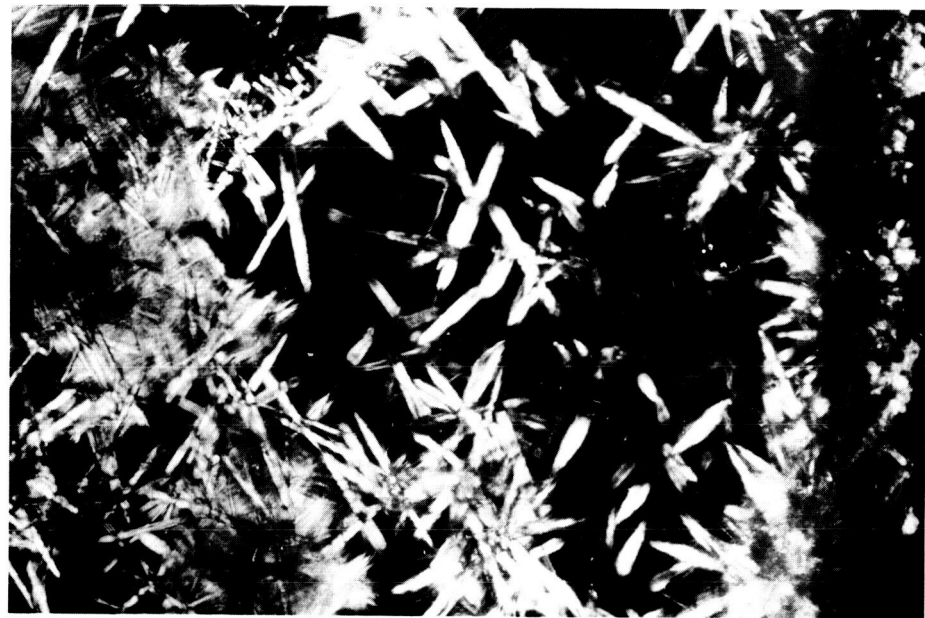
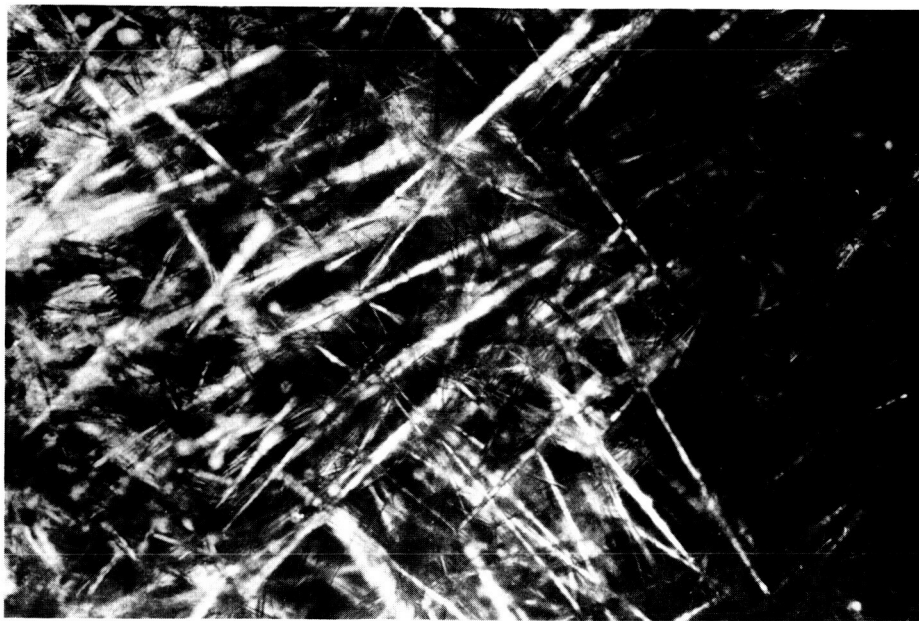


FIGURE 5 NEEDLE-LIKE QUENCH CRYSTALS



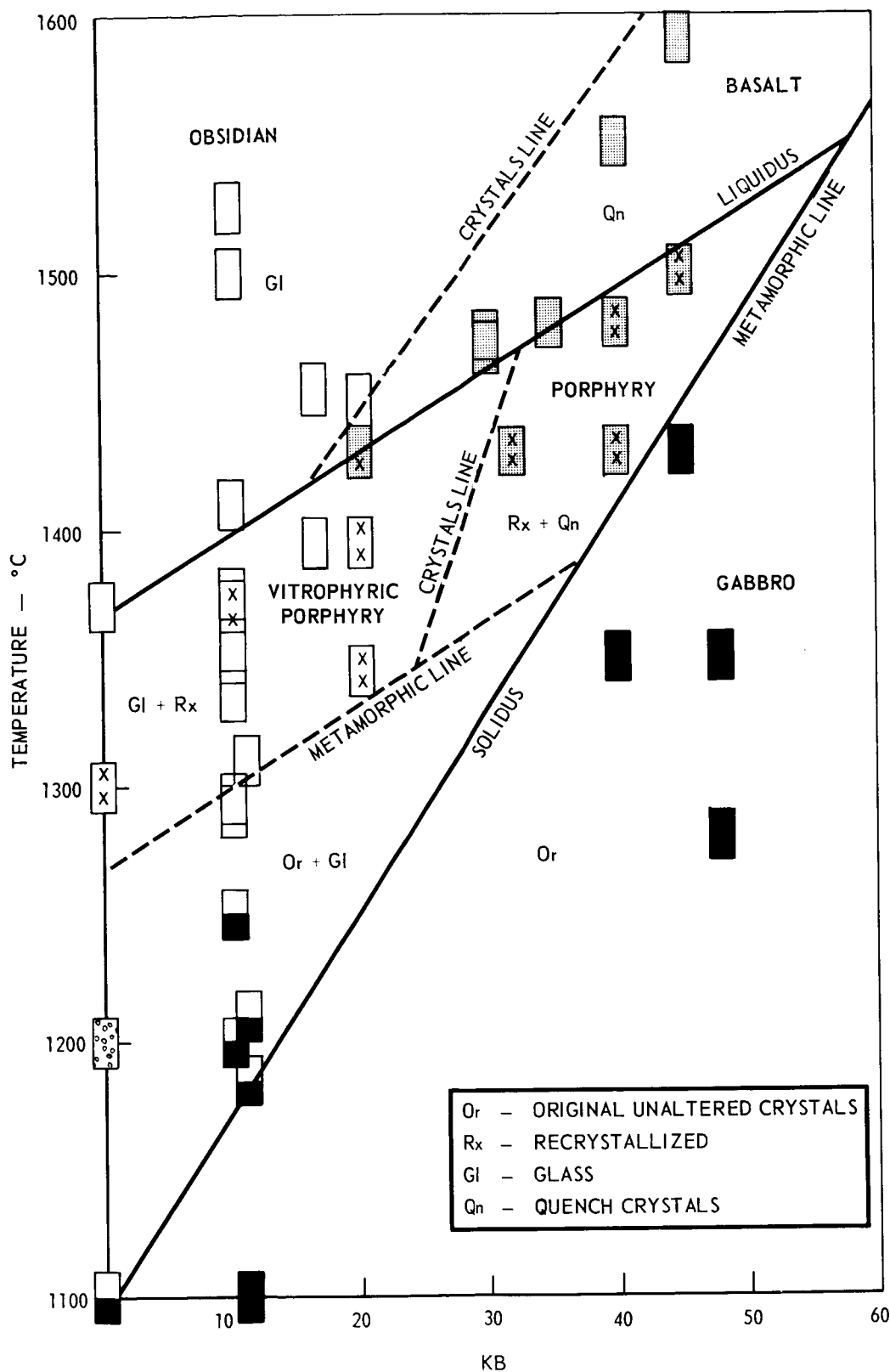


FIGURE 6 MELTING RANGE OF A GABBRO AT HIGH PRESSURES;  
 SUPERIMPOSED IS A GENETIC DIAGRAM SHOWING SEVERAL  
 PRESSURE-TEMPERATURE AREAS WHERE THE GABBRO USED AS  
 AN INITIAL SAMPLE WOULD QUENCH INTO NEW ROCKS.  
 PATTERNS: BLACK — UNALTERED CRYSTALS; WHITE = GLASS;  
 DOTTED — QUENCH CRYSTALS; XX = RECRYSTALS